Orissa Journal of Physics
ISSN 0974-8202

Vol.30, No. 1
February. 2023
pp. 1-6

Disorder magnetic system: Spin glass

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Received 11.12.22, Accepted 7.1.23

Abstract: The Nobel Prize in Physics for the year 2021 has been shared by three laureates for their ground breaking contribution to the understanding of complex physical systems [1]. While one half of the prize goes to Syukuro Manabe of Princeton university USA and Klaus Hasselmann of Max Planck Institute of Meteorology, Hamburg, Germany for their foundational work on “Physical modelling of Earth’s climate and reliably predicting global warming", the other half goes to Giorgio Parisi of Sapienza University of Rome, Italy for his revolutionary contribution to the understanding of disorder and random phenomena in complex materials. Systems characterised by randomness and disorder are complex to comprehend. The principles underlying the observed behaviour of such systems are not clear. Giorgio Parisi’s best work was on disorder magnetic system– “spin glass”, which is a prototype complex system. This article delineates the subtle characteristic of spin glass as compared to ordinary magnets that we encounter in our day-to-day life and reflects the noteworthy contribution of Giorgio Parisi that brought him acclaim.

Keywords: Paramagnet, Ferromagnet, Symmetry breaking, Spin glass, and Frustration

PACS Number: 75.00.00, 75.25.+z, 75.50.Lk, 75.10.Nr

Introduction: Giorgio Parisi was born in Rome, Italy, in the year 1948. His father and grandfather were construction workers, but young Parisi was always fascinated by the complicated abstractions in Mathematics and Science. He wanted to pursue his career in Science because it was challenging. He obtained his PhD in Physics from the University of Rome in 1970, and subsequently worked as researcher at the National Laboratory of Frascati for 10 years, 1971-1981. He became a full professor at the University of Roma II, Tor Vergata, in Rome in the year 1981. In 1992, he moved to the University of Roma I, La Sapienza, in Rome as a professor of quantum theories, where he remains till today. Parisi’s research activity covered a spectrum of fields that include elementary particles, mathematical physics, disorder systems, non-equilibrium statistical mechanics, and computer science. Arguably, his best work involves the understanding of the complexity in the random magnetic system– “spin glass” [2,3]- a field which he stumbled upon in 1978. Researchers in the 1970s struggled a lot to understand the complex phenomena involving spin glass. But the results surrounding the theoretical models were inconsistent with the general expectation based on known laws. At this time Parisi entered the spin glass fray and with his ingenious mathematical manoeuvre, he helped to resolve the puzzle surrounding the theoretical models and provided an exact solution in 1979 [4]. His work forms one of the important breakthroughs in the history of disorder system.

Paramagnet-ferromagnet transition (symmetry breaking): Before delving directly into the understanding of spin glass, let us take an easy ride to understand the characteristic magnetic property in ordinary magnets that we encounter in our day-to-day life. The origin of magnetism in solids mainly arises from an intrinsic quantum mechanical property of the electron called “spin” which has no classical analogue. This is because even though spin possesses mathematical characteristics like angular momentum, it does not arise from any real angular motion as angular momentum does. But, it behaves like a permanent bar magnet having an intrinsic magnetic dipole moment (spin magnetic moment). In an ordinary ferromagnet like Iron, the spins at each atomic site align parallel with neighbouring spins below a characteristic temperature known as Curie temperature (T_C) and results in a finite magnetisation for the substance. However, as the temperature gradually rises above the Curie temperature, spins increasingly jostle, gyrate, and fluctuate because of thermal agitation and the spin at each atomic site points in different random directions at each instant of time. Since all the spins are randomly oriented and have no correlation with each other, the overall magnetisation at any time is zero and we define it to be a paramagnet (spin-disorder phase). The schematic illustration of spin arrangement for ferromagnet and paramagnet is shown in Figure.1.

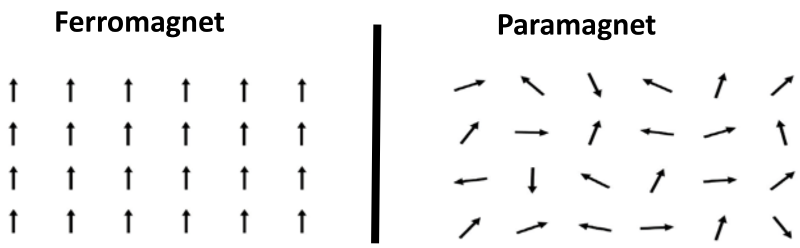

Fig.1. Schematic illustration of spin arrangement for a ferromagnet (spin-order phase) and a paramagnet (spin-disorder phase). The arrows indicate the spin magnetic moment at each atomic site.

The appearance of spontaneous order (alignment of spins) at low temperature in case of a ferromagnet arises as a consequence of symmetry breaking. To understand what we mean by symmetry breaking, let us take the example of water (liquid) to ice (solid) transition when it is cooled down. The atoms in a liquid have all degrees of translational and rotational symmetry. This is to say, any point in the liquid is exactly the same as any other. However, for a solid there exists special directions in which the atoms are lined up, and can have translation only by an integer multiple of a minimum distance (lattice constant). This is akin to a crowd exhibiting chaotic distribution of positions in a market place and a crowd standing in a queue. Therefore, the symmetry associated with the solid is less as compared to the liquid and we say “symmetry is broken” when a liquid freezes into solid. Akin to liquid-solid transition, the paramagnet-ferromagnet transition is driven by rotational symmetry breaking in spin space. In the paramagnetic case, each magnetic moment can point in any direction (rotationally invariant) like people in a market place, but a fixed direction is singled out for all spins below T_c in the ferromagnetic phase like people in a queue. Symmetry breaking has been the central paradigm in physics to understand the organisation principle in many physical systems.

Spin glass: The term “spin glass” was coined in the early 1970’s to describe distinct class of disordered magnetic state in which the spin magnetic moment at each atomic site is frozen in a particular direction, but with the essential provision that the frozen alignment direction varies randomly between atoms [2,3]. By the beginning of 1970, scientists in the condensed matter community were curious to know as to what kind of magnetic state emerges when a few percentage of magnetic impurity such as iron (Fe) or manganese (Mn) are randomly mixed into the nonmagnetic noble metal such as gold (Au) and copper (Cu)) as shown in Figure.2. Initial experimental results on gold-iron alloy in 1972 presumably signalled a phase transition from high-temperature paramagnetic phase to a low-temperature phase with some sort of magnetic ordering (spin ordering)[5]. However, subsequent sensitive experimental probes indicated the absence of any long range global magnetic ordering and the overall magnetization was zero. More importantly, it was found that spins at magnetic impurity sites are stuck (frozen) in random orientations unlike the paramagnetic spins that fluctuate randomly. The frozen spin state was unique and neither was representing a paramagnetic, ferromagnetic or any kind of magnetically ordered state. Such frozen magnetic state in AuFe and CuMn alloys was termed – spin glass. It is to be noted that even though there are only a few percentage of magnetic impurity in a spin glass, they change the materials' magnetic properties in a radical manner. A schematic representation of AuFe spin glass is depicted in Figure.2. The term "glass" appears by an analogy with ordinary glasses e.g. a window glass in which the atoms are positioned randomly and does not have an orderly crystal structure. Similarly, in a spin glass the impurity magnetic spins are frozen randomly and it does not have any orderly magnetic structure.

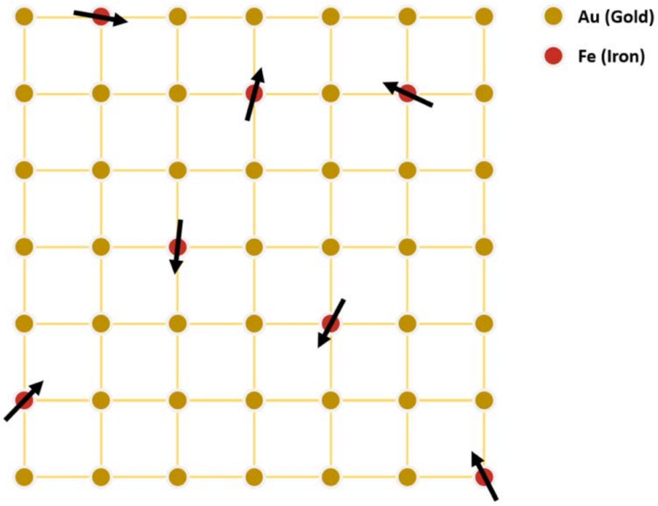

Fig.2. Schematic illustration of AuFe spin glass in which the iron atoms as magnetic impurities are mixed randomly to the nonmagnetic gold matrix. The spins associated with iron atoms represented by arrows are trapped in random directions.

The freezing of spins represents that the spin glass should be ordered in time. This is to say that if we measure a spin on a particular site pointing in a particular direction at an instant of time and wait for an arbitrarily long time, we still see it to be pointing in the same direction. Naively, if we take a snapshot of a particular spin and wait for an arbitrary long time and then take a second snapshot, both snapshots look the same. Though this is also true for a ferromagnet, it is the absence of spatial or positional magnetic order coupled with ordering in time that makes spin glass unique. The freezing of spins and the absence of spatial long range magnetic order with respect to positions together constitute most prominent features of spin glasses.

The underlying essential ingredients for spin glass is frustration and randomness/disorder (random distribution of magnetic ions). By frustration one means that not all of the constraints on a given system can be physically realised simultaneously. A striking generalised example of a completely frustrated system is a triangular one with all antiferromagnetic interactions as shown in Figure 3. Imagine a triangle with spins placed on three corners. Now we impose an "antiferromagnetic" constraint that any adjacent pair must have the opposite orientation. Once two adjacent spins are oriented antiparallel to each other, the third one runs into a state of complete confusion as to which direction to orient! This is like if you want to befriend two people at the same time, but they hate each other, then you run into a frustrating situation. In terms of energy consideration, it will not make any difference whether the third spin points up or down in the frustrated triangular lattice. The problem then arises how then one finds an optimal orientation of spins state that minimises the frustration in real materials. Which spin should be chosen to be frustrated or are there possibly many minimum energy states? What should be the global pattern for spin orientation? This is one of the central problem in the spin glasses. Giorgio Parisi in 1979 found a solution to this puzzle by realizing that there could be infinite number of states with optimal orientation within the spin glass phase [4,6] in contrast to the case for a simple ferromagnet in which the all the spins are arranged either in up or down directions. This means that the nature of symmetry breaking in the spin glass is very different from what we learned in case of paramagnetic-ferromagnetic transition. Since spin glass possess many (metastable) states with equivalent energy states, they are unable to access equilibrium in an experimental time scale, and thus exhibit a plethora of dynamical behaviours with time.

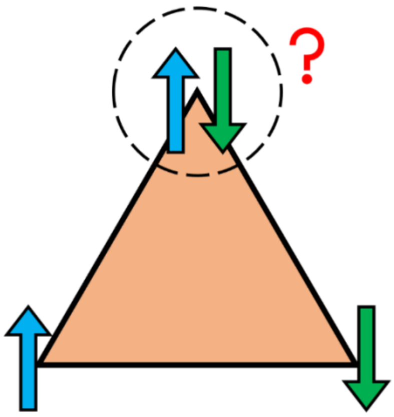

Fig.3 depicts frustration in an antiferromagnetic triangular lattice i.e. when one spin points upward and the other downward, the third spin remains in a state of confusion as it cannot satisfy both of them simultaneously since adjacent spins prefer to point in opposite directions because of antiferromagtic constraint.

Conclusion: The field “spin glass” today is broad and has connectivity to different threads and sub-threads of research involving random complex materials and phenomena. The mathematical description, conceptual tools and ideas developed by Giorgio Parisi and others for the understanding of the structure of spin glasses over the years have found its successful applications in a variety of other fields such as neural network, protein folding, and computer design. The human brain is the most complex organ in the human body and it helps us to think, understand, and make decisions. Neural network is a model to understand how the brain that consists of billions of randomly interconnected neurons functions or how a concept is formed in the brain from the firing activities of a collection of randomly connected neurons. Proteins characterised by long chain of biomolecules are the building blocks of life and responsible for most of what happens inside cells. How a protein works is determined by its three dimensional structure resulting from the folding of a protein. The folding of a protein is a complex process. The knowledge gained in the field of spin glass has been very much effective to provide new ways of thinking to address the problems involving neural network, protein folding. The 2021 Nobel Prize in Physics is thus a recognition of human effort in understanding principles underlying the random and complex systems; be it in physics or biology or climatology.

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